MARINE RESERVES AND THE RESTORATION OF FISHERIES AND MARINE ECOSYSTEMS IN THE SOUTH CHINA SEA

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ABSTRACT

The South China Sea has been devastated by human fishing. This paper reports an initiative to restore Hong Kong's marine ecosystems and fisheries through the deployment of artificial reefs (ARs) within marine protected areas (MPAs). Current catch and biomass data by species and fishery sector were available. Quasi-spatial ecosystem simulations, using a modified ECOSIM method, have been employed to forecast benefits from a successful MPA/AR system. Results indicate that, despite increasing fishing power in the Hong Kong fleet, a 10–20% MPA/AR system could provide significant benefits within 10 yrs, and shifts to low-value pelagic fish could be reversed. Approximate scores, expressing how species benefit from protected ARs, suggest that results are not biased by changes in species composition. The design of MPA/ARs balances island biogeographic theory with the needs of monitoring and compliance: minimizing perimeter losses and establishing colonizing corridors are trade-offs with statistical replication and monitoring, whereas sacrifice of some ARs to fishing encourages compliance and learning. In Hong Kong, workshops with fishing communities encouraged support. Bioeconomic analysis shows an MPA/AR system increasing fishery value, but noncompliance rapidly erodes benefits. The benefits of this approach are assessed together with problems and difficulties that have arisen.

The marine ecosystem of the South China Sea is one of the most heavily affected by human fishing in the world (Pauly et al., 1996; Silvestre and Pauly, 1997). In Hong Kong, one of the few South China Sea locations where fisheries have been assessed quantitatively, the effects of uncontrolled trawling on benthic structure and fauna have been immense (Leung and Lee, 1987; Wu, 1988; Gomez et al., 1990), catches have declined markedly over the past 10 yrs (Richards, 1985; Richards et al., 1985; Cook et al., in press), and fishing mortality rates are extremely high in seven gear sectors (Pitcher et al., 1998). Trawling has large effects (Valente et al., 1996): for example in Tolo Harbor each square meter may be trawled three times a day (K. Wilson, pers. comm.). Consequently, the biomass of long-lived, high-value demersal fish species has been greatly reduced, if not eliminated from many areas, and the species composition has shifted toward low-value, short-lived pelagic fish, a dismal example of "fishing down the food web" (Pauly et al., 1998a), also reported from the nearby East China Sea (Chen et al., 1997). Opportunities for mitigating and reversing this depressing state appear slim (Heinke, 1996). Misreported and unreported catches are rife, and capture fisheries management has been effectively absent (Lai and Yu, 1995). Many of us fear that, if action is not taken, the oceans over much of our planet may slowly come to look like the South China Sea (Pauly et al., 1998b).

Here, we report an attempt to turn the tide. In the South China Sea, devastation has proceeded so far that merely to mitigate the present depletion appears pointless: a policy goal of sustainability ("sustaining the present misery," Pitcher and Pauly, 1998), seems inappropriate. Within the Special Administrative Region (SAR) of Hong Kong, the political will, administrative ability, and legislative instruments that may regulate fishing and restore the environment appear to be in place (ERM, 1997; Patten, 1997). The work attempts practical implementation of a restoration ecology of the oceans (Pitcher, in press), where the policy goal is to rebuild resources that are embedded in whole ecosystems, as opposed to conventional fisheries rebuilding, which is largely confined to single-species perspectives. Modeling to support rebuilding is shaped and constrained by the "Back to the Future" process, the model reconstruction of past ecosystems (Pitcher, 1998), and "Ecoval," the comparative evaluation of the benefits of alternative ecosystems (Pitcher et al., in press). Although we face a large number of uncertainties in a highly species-rich environment, the work in Hong Kong reported here represents a first step in that process.

Background to MPAs and ARs in Hong Kong

In 1994 the Hong Kong government decided to implement an evaluation plan for local fisheries (Wilson and Cook, 1998). Since 1997, the Hong Kong SAR has continued that plan into a mitigation, restoration, and community-outreach phase (ERM, 1997). The Fisheries Centre at the University of British Columbia has been involved in both of these stages, along with partners in Hong Kong's government, university, and private sectors. (The two projects have involved Environmental Resources Management Ltd.; Furano Ltd.; Hong Kong City University; the University of Hong Kong; the Southampton Oceanography Centre; Babtie, Harris and Sutherland Ltd.; and the Agriculture and Fisheries Department of the Hong Kong SAR Government.) Marine protected areas (MPAs) have been included in the project to reduce fishing and allow recovery of stocks. They are termed 'Marine Special Areas' in Hong Kong to allow a legislative basis for control (ERM, 1999). Artificial reefs (ARs) are being considered for Hong Kong MPAs because much reef habitat has been destroyed, and stock recovery needs a kick start (Wilson and Cook, 1998). It is realized that ARs without MPAs are dangerous to recovery because they may serve only to concentrate fish resources (see, e.g., Polovina, 1989), which can then be fished out more easily, and that, in Hong Kong, MPAs without ARs (see Allison et al., 1998) would probably not attract and conserve valuable reef species that have been almost wiped out. Moreover, legislation to support the establishment and protection of the MPA/ARs with statutory controls as Marine Special Areas in Hong Kong is being enacted (ERM, 1999), overseen by the Agriculture and Fisheries Department (see Cook, 1994). Recovery after protection is rapid for many fish species in these tropical inshore waters, as evidenced by the early colonization of sunken-vessel ARs already placed in a Marine Park in Hong Kong (Leung et al., 1995).

Methods

Fishery Catches and Fish Biomass.—Estimates of the 1996 Hong Kong biomass and catch by seven gear sectors were available for 152 species: full details of the surveys and assessment methods are presented elsewhere (Pitcher et al., 1998). The estimated catch by sector, including confidence limits, is given in Table 1. The present annual catch is some 15,000 mt, about 8 mt km^{-2}), of which over 40% are small pelagics, caught by about 2500 vessels. In Hong Kong, both large-scale and small-scale fishers are fishing heavily enough to have significant impacts on both biomass and biodiversity. Over half the catch by weight and by number of species is made by the 10% of the fleet

Table 1. Estimated annual catch by gear sector in the Hong Kong fishery in 1996, together with 95% confidence limits (CL). Catches are estimated from mean annual catch per species and per vessel type from log normal distributions of catch rates. Number of vessels of each type fishing in Hong Kong waters and number of species caught are estimated from vessel surveys and catch interviews. Misc = vessels that operate different gear types (longline, handline, gill net, cage traps); P4/7 = small vessels operating mainly handline and traps.

	Estimated catch (mt yr^{-1})			Mean catch	Number of	Number of
	Lower 95% CL	Mean	Upper 95% CL	per vessel (mt yr^{-1})	vessels fishing	species reported
Shrimp trawl	245	879	3,930	4.9	191	58
Hang trawl	440	1,293	5,276	38.8	36	22
Stern trawl	178	572	3,388	17.6	33	55
P4/7 boats	909	3,964	23,903	2.0	1,680	105
Misc boats	748	2,842	17,157	6.3	403	96
Pair trawl	985	1,563	260,512	170.4	15	18
Purse seine	630	3,633	48,556	33.1	135	46
Total	4,134	14,747	362,722	3.0	2,492	152

comprising the industrial sector, but 46% of the catch by weight and 80% of the species caught come from over 3500 small vessels operating a great diversity of hand gear types. Twelve out of 13 fish species for which single-species stock assessments were performed were in the U.N. Food and Agriculture Organization's "over-exploited" category, whereas one fish species and four benthic crustaceans were assessed as "fully exploited." Total fish biomass in Hong Kong varies seasonally between about 10,000 and 27,000 mt (5–15 mt km^{-2}), 60% of which are small pelagics. This biomass, like those of other parts of the South China Sea, is considerably lower than those of many other inshore marine areas (Pitcher et al., 1998).

Ecosystem Simulation Methods.—Our approach to the analysis of the impact of fishing in Hong Kong's multispecies fishery is based on trophic structure as revealed by the mass-balance ECOPATH system (Christensen and Pauly, 1992), which has been widely applied to aquatic ecosystems (see contributions in Christensen and Pauly, 1993, and http://www.ecopath.org). ECOPATH itself provides a static picture of ecosystem trophic structure, answering the question, 'What trophic flows support the current ecosystem trophic structure and are consistent with observed growth and mortality?'—but our main analytic tool has been ECOSIM, a system of coupled differential equations that can be used for dynamic simulation and analysis of alternative scenarios (Walters et al., 1997) and can answer 'what if?' questions. In the past, fisheries work has ignored the ratchet-like processes that erode biodiversity and the value of aquatic resources (Pitcher, in press), and many have called for an ecosystem basis to management (e.g., Larkin, 1996; Botsford et al., 1997). Marine reserves are an obvious device to consider (Bohnsack, 1993, 1996; Clark, 1996; Guénette et al., 1998; Lauck et al., 1998), but their impact must be assessed on an ecosystem basis. The transition from single-species to ecosystem modeling has also been discussed for terrestrial reserves (Simberloff, 1997). Implicit in our modeling is that recovery of stocks within the MPA/ARs will increase catches outside them (Russ and Alcala, 1996a). Despite considerable uncertainty about the simulation of ecological processes, we believe that the important questions can be tackled only by means of an ecosystem-based methodology. The methods used here represent a first step.

The ECOPATH mass-balance model for Hong Kong was refined from that used in previous work, which was, in turn, based on earlier South China Sea work (Pauly and Christensen, 1993) and work in the Brunei Darussalam coastal area, south of Hong Kong (Silvestre et al., 1993). Full details are presented elsewhere (Pitcher et al., 1998), but where not otherwise mentioned, data came from our own survey material. The mass-balance model comprised 16 functional groups (biomass pools), in addition to phytoplankton, zooplankton (based on Nguyen, 1989; Plyakarnchana, 1989; Aryuthaka, 1991), and detritus (Table 2). The biomass of these ecosystem components in the mass-balance model is shown in Table 3, which also summarizes the other model parameters. Diets and

Table 2. Taxonomic groups used in the Hong Kong mass-balance model in addition to zooplankton, phytoplankton, and detritus. Derivation of parameters for each group is described by Pitcher et al. (1998).

Group	Species included	Comments
Penaeids	Penaeidae: *Metapenaeopsis barbata*, *M. palmensis*, and all other penaeids (*Metapenaeopsis*, *Penaeus*, *Solenocera, Parapenaeopsis*); Sergestidae including *Actes japonica* (silver shrimp)	Diet based on Liao and Su (1984)
Benthic crustaceans	*Panulirus* (lobster), *Charybdis, Harpiosquilla, Dictyosquilla, Oratosquilla*, *Scylla* (mangrove crab), and *Portunus*; all penaeid benthic crustaceans like mantis shrimp (Squillidae: *Harpiosquilla, Oratosquilla*) and Solenoceridae (mud shrimp)	
Benthic molluscs	Arcidae: *Anadara* (cockle); Veneridae: *Tapes* (clam); Buccinidae: *Babylonia* (whelk)	
Small zoobenthos	Small macrobenthos and meiobenthos (Foraminifera, Nematoda, Harpacticoida, Ostracoda, Turbellaria, Copepoda, Ciliata, Gnathostomulida, Gastrotricha, Polychaeta, Oligochaeta, Kinorhyncha, Mystacocarida, Cephalocarida, Tanaidacea, Bryozoa, Cnidaria, Sipunculida, Nemertina, and Tardigrada)	From the commercial catch only unidentified sea urchins (parameters based on information from Thompson et al., 1980; Shin and Thompson,1982; Sarma and Wilsanand, 1994).
Cephalopods	Includes octopus, all Loliginidae (*Loligo edulis*, *Loligo* sp., *Sepioteuthis lessoniana*), squids, Pinnidae (*Pinna bicolor*, fan mussel), Sepiidae (*Sepia pharaonis*, *Sepia* sp., cuttlefish)	
Elasmobranchs	Sharks: bamboo sharks, *Chiloscyllium*; wobbegong; *Orectolobus*; *Carcharhinus*), rays (*Dasyatis, Raja,* and *Gymnura*)	Many sharks are reported from Hong Kong waters (Chan and Tseng, 1982; Compagno 1984a,b), residents are rare today; the catch (and model) are dominated by rays.
Small demersal fish (< 30 cm)	Ambassidae, Apogonidae, Carangidae, Clupeidae, Cynoglossidae, Gerreidae, Gobiidae, Leiognathidae, Mullidae, Nemipteridae, Pomacentridae, Sciaenidae, Scorpaenidae, Serranidae, and Siganidae. Some information from Chan and Tseng (1982).	
Medium demersal fish (>30 cm, < 50 cm)	Carangidae, Drepanidae, Lutjanidae, Monacanthidae, Mugilidae, Muraenidae, Nemipteridae, Plotosidae, Polynemidae, Scatophagidae, Sciaenidae, Serranidae, Sillaginidae, Sparidae, Stromateidae, Synodontidae, and Theraponidae	

Table 2. Continued

Group	Species included	Comments
Large demersal fish (> 50 cm)	Carangidae, Haemulidae, Lethrinidae, Lutjanidae, Mugilidae, Muraenesocidae, Paralichthydae, Platycephalidae, Sciaenidae, Sparidae, Stromateidae, Synodontidae, and Trichiuridae	The larger snappers and croakers, etc.
Migratory demersals	Sparidae; *Pagrus major,* red seabream or red pargo	A few species whose Q values (ca 3) seem more pelagic than demersal (7 to 16)
Pelagic fish	Carangidae, Centrolophidae, Cheilodactylidae, Clupeidae, Engraulidae, Haemulidae, Kyphosidae, Sciaenidae, and Scombridae	
Migratory pelagics	Clupeidae (herrings): *Clupanodon punctatus*, *Hilsa* spp.; Scombridae (mackerels): *Scomber commerson*, *S. guttatus*, *S. japonicus*, *Scomber* spp.; Sphyraeniodae (barracuda): *Sphyraena* sp.; Synodontidae (bombay duck): *Harpadon nehereus*	
Marine mammals	Ginkgo-toothed beaked whale (*Mesoplodon ginkgodens*), Indo-Pacific humpback dolphin (*Sousa chinensis*), rough-toothed dolphin (*Steno bredanensis*), Pacific white-sided dolphin (*Lagenorhynchus obliquidens*), bottlenose dolphin (*Tursiops truncatus*), pantropical spotted dolphin (*Stenella attenuata*), striped dolphin (*S. coeruleoalba*), common dolphin (*Delphinus delphis*), and finless porpoise (*Neophocaena phocaenoides*)	List from Jefferson et al. (1993). According to Jefferson (1997), 100 humpback dolphins and 150 finless porpoises reside in Hong Kong.

Table 3. Mass-balance model parameters for the 15 ecosystem groups used as starting values for the Hong Kong ecosystem simulations. Biomass is average mt km^{-2}, catch is mt km^{-2} yr^{-1}. Some parameters, for example trophic level, were estimated by the mass-balance model; others are input. P/B = production-to-biomass ratio; Q/B = consumption-to-biomass ratio; EE = ecotrophic efficiency. The table shows the number of fish species included in the Hong Kong catch database alongside the numbers of species known to be present in Hong Kong but not in the catch.

Group	Biomass (mt km^{-2})	Catch mt km^{-2} yr^{-1}	P/B yr^{-1}	Q/B yr^{-1}	EE proportion	Trophic level	# spp. in catch	# spp. not in catch
Phytoplankton	13.00	-	231.0	-	0.89	1.0	-	-
Zooplankton	17.30	-	40.0	192.0	0.50	2.1	-	-
Penaeids (prawns)	0.04	0.16	7.0	30.0	0.95	2.8	15	7
Benthic crustaceans	0.46	0.60	7.0	30.0	0.95	2.8	12	2
Benthic molluscs	1.09	0.01	3.4	50.0	0.95	2.9	5	2
Small zoobenthos	35.20	0.01	5.5	30.0	0.39	2.0	-	-
Cephalopods	0.40	0.35	2.0	7.3	0.95	3.6	8	0
Elasmobranchs	0.06	0.01	0.3	7.0	0.72	3.3	3	0
Small demersal fish	1.07	3.23	4.0	15.0	0.95	2.8	31	26
Medium demersal fish	0.88	1.66	3.5	8.0	0.95	3.1	32	28
Large demersal fish	0.04	0.25	2.0	5.5	0.65	3.9	21	19
Migratory demersals	0.28	0.01	2.5	10.0	0.95	3.4	2	0
Pelagic fish	0.65	1.12	4.5	15.0	0.95	3.1	15	15
Migratory pelagics	0.52	0.17	2.2	10.0	0.95	3.5	8	6
Marine mammals	0.01	-	0.3	40.0	0.00	3.8	(9)	-
Totals	70.99	7.58	-	-	-	-	152	103

parameter values for each component were obtained from the literature, as described in detail elsewhere (Pitcher et al., 1998). The model was balanced as described by Christensen and Pauly (1992) and further tuned to estimated fish biomass values from the survey.

QUASI-SPATIAL DYNAMIC ECOSYSTEM SIMULATIONS.—Modifications were made to the ECOSIM ecosystem-simulation method (Walters et al., 1997) to allow biomass for each ecosystem component to be split in a quasi-spatial way. Technical details are given by Watson and Walters (1998). The method is simpler than spatially explicit modeling (ECOSPACE, Walters et al., 1999), which was first implemented after we completed this work. Currently, the quasi-spatial model can provide more structured outputs of the likely benefits against MPA size.

In this method, each biomass pool from an ECOPATH mass-balance model is divided into two portions that can be subjected to different fishing patterns, as if they were spatially separated. This method allows for one part to be modeled as a no-take MPA while the other is subject to fishing mortality. Fishing patterns can be shaped sector by sector to simulate a wide range of changes in fishing pressures. The rate of migration or transfer of biomass between the two parts of each biomass pool can be set individually. For example, if the MPA size is set at 0.05, then 5% of the initial biomass of each component in the ECOPATH model of Hong Kong will be inside the modeled MPA. Therefore, for each ECOPATH biomass pool, j:

$$\text{Biomass}_{j,\text{MPA}} = (\text{Proportion of system as MPA}) \times (\text{Biomass for ECOPATH pool j})$$

$$\text{Biomass}_{j,\text{non-MPA}} = (\text{Biomass for ECOPATH pool j}) - \text{Biomass}_{j,\text{MPA}}$$

The rate of biomass exchange, representing migration, between the subpools of the MPA and non-MPA is determined by two factors in the model—first a user-supplied rate of migration value and second the portion of the total area that the subpool occupies. The migration-rate model reflects the larger ratio of perimeter to area of smaller MPAs; in smaller areas animals are more likely to cross the MPA boundary and move out into the fishery. If P is the proportion of the fishery area that is an MPA, and M is a user-supplied migration-index value, then the migration rates in and out of the MPA area for a biomass pool, j, can be represented as:

$$\text{Migration}_{\text{j,MPA to non-MPA}} = \text{M}\big/\sqrt{\text{P}}$$

$$\text{Migration}_{\text{j,non-MPA to MPA}} = \text{Migration}_{\text{j,MPA to non-MPA}} \times \left(\text{P}\big/\left(1-\text{P}\right)\right)$$

The rates into and out of the MPA have to be in equilibrium (regardless of the MPA size) before we make changes to the system, such as fishing only outside the MPA. The rate of movement out is $M/\sqrt{(P)}$, and the balancing movement in is $M/\sqrt{(P)} \times (P/(1 - P))$, which reduces to $M \times (P/(1 - P))$. This is a binomial term because, as the proportion in the MPA pool gets smaller, the non-MPA pool must become larger because $P + (1 - P) = 1$. The rate of immigration must balance the emigration in absolute biomass terms, and therefore the proportional rate, which is expressed as a proportion of the biomass per area, must be prorated by the relative area of the MPA (P) and non-MPA (1 – P) areas.

We do not have actual movement rates of the species comprising the ECOPATH pools for Hong Kong that could be used for our MPA simulations. We therefore assumed that groups containing more sedentary species, for example 'benthic molluscs', would have lower migration rates than other groups such as 'migratory pelagics'. Trials with ECOSIM demonstrated that the predicted impact of MPAs changed with the assumed overall migration rates for the biomass pools. To demonstrate the sensitivity of subsequent biological and economic results to assumed migration rates, we used rates considered to yield slow, medium, and fast movement for the organisms involved (Table 4). In this paper only the results from the slow and fast assumptions are presented; the medium results were intermediate in each case.

Animals like sea cucumbers do not move at the same rate as tuna and would therefore probably not move out of an MPA at the same rate (regardless of the MPA size). A value of $M = 0$ implies no transfer at all between the MPA and non-MPA areas. In practice, values $M < 0.1$ produced very little exchange, whereas $M > 5$ made the MPA very 'permeable', and biomass moved very freely. Accordingly, in the 'fast' schedule of rates in Table 4, the rates for each ECOPATH model group maintained their natural relative rankings by taxa, and M caused a rate of exchange under which even moderately mobile animals were moving out of the MPA. In the 'slow' scenario, even migratory animals had some protection from fishing. We believe that these two extreme scenarios more than encompass the likely natural range of movements. In practice, the monitoring of MPAs could be designed to allow estimates of these rates from observations or tagging programs.

Our simulations were based on the assumption that no fishing took place inside the MPA/AR area. The MPA biomass subpool was therefore not subject to fishing mortality, and all fishing mortality and harvests were assumed to come from the non-MPA area. As the MPA/AR size was increased from 0 to 20% of the total area, fishing became concentrated in a decreasing fraction of the current fishing grounds. It was assumed that fishing mortality would not decrease as the size of the MPA increased, because without additional regulatory instruments, we did not anticipate any decrease in either fishing effort, catchability, or efficiency outside of the MPA area simulated. Therefore, fishing mortality increased in the fished area in order to maintain the overall level of fishing mortality.

Quasi-spatial ecosystem simulations were produced for MPA sizes ranging from 0.5 to 20% of the total Hong Kong area over a period of 30 yrs. It was assumed that, over this time, in the absence of mitigating measures such as MPA/ARs, increasing fishing pressures would cause some degradation in the fisheries of Hong Kong. We believe this is the safest and most precautionary assumption

Table 4. Migration indices (M, dimensionless) used for MPA modeling of ecosystem biomass pools in the quasi-spatial ECOSIM simulations. For full discussion of the rates, see text.

ECOPATH Group	Slow	Medium	Fast
Phytoplankton	0.1	0.2	0.4
Zooplankton	0.1	0.2	0.4
Penaeids	0.5	1	2
Benthic crustaceans	0.5	1	2
Benthic molluscs	0.5	1	2
Small zoobenthos	0.5	1	2
Cephalopods	1	2	4
Elasmobranchs	1	2	4
Small demersal fish	1	2	4
Medium demersal fish	1	2	4
Large demersal fish	1	2	4
Migratory demersals	2	4	8
Pelagic fish	1	2	4
Migratory pelagics	2	4	8
Marine mammals	2	4	8
Detritus	0.1	0.2	0.4

for our analysis, especially when an economic analysis must include discounting of future streams of benefits. We therefore used an annual rate of increase in fishing mortality based on historical records. A decrease in annual catch for Hong Kong waters of 21% over 7 yrs between 1989 and 1996 has been documented (Cook et al., in press), so our simulations used an annual increase in fishing mortality of 3% over the period simulated.

Reef Response Index (RRI): An Assessment of Species Responses to ARs.—Individual species will benefit differentially from the ARs, but the ecosystem simulation method necessarily uses pools of species. Were the responses of these pools biased because some species did better than others in the ARs? For example, reef-associated fish species with a vestigial presence in Hong Kong, but not currently recorded in the catch, might recover sufficiently to appear in the catch. On the other hand, the present ecosystem model pools might be biased against reef species. To answer this question we devised a scoring technique for a Reef Response Index (RRI), intended to express the rate at which species' biomass would recover.

Our method assumes that species that depend on rocky reefs for at least one stage of their life history are likely to benefit from ARs. The scoring method also required that we make some assumptions about the circumstances in which the AR would be deployed, as well as the role that an AR would play in the life history of the species under consideration. For example, when relief structures and/or rocky bottoms are limiting, some species may be aided by artificial reefs; an example is the increase in octopus population around Japan when ARs were deployed (Bohnsack et al., 1997). For our purposes we assume that ARs would be set on soft sediment zones, because hard-bottom and soft-bottom food resources are thought to be linked for several species (Frazer and Lindberg, 1994). We also assumed that ARs would be complex structures providing a wide range of shelter sizes and crevices to accommodate both juveniles and adults.

We assessed the potential benefit for each species, using ranked scores for six life-history and behavioral attributes: home range, fidelity to reefs, spawning, nurseries, feeding, and refuge (Table 5). Species depending on reefs at every stage would have the highest total score, obtain the maximum benefit from the AR, and have the greatest change in productivity and subsequently catch. Sedentary species, especially those dependent on reefs, are good candidates. We assigned average scores to each family but found that differences in the life-history patterns of species within families required us to attempt to score all the major commercial species (255 in our Hong Kong data-

Table 5. Scoring criteria used to estimate Reef Response Indices applied to the species mix of potential catches by ecosystem group. The maximum score of 24 was equated to 100%, and other totals scaled accordingly.

Life-history attribute	Scoring criteria
Home range	4. Sedentary or only refuge-feeding movements
	2. Moderately migratory
	0. Migratory, e.g. sardines
Fidelity to reefs	4. Loyal or travel from reef to reef (<5 km)
	2. Moderately loyal (present part of the year)
	0. Transient
Spawning	4. Use reefs
	2. May use reefs
	0. Do not use reefs
Nurseries	4. Use reefs
	2. May use reefs
	0. Do not use reefs
Feeding	4. Reef-dependent
	2. Commonly use reefs
	0. Opportunistic
Refuge	4. Reef-dependent
	2. Seldom use reefs
	0. Do not use reefs

base) individually. When only the genus was mentioned (e.g., *Gymnothorax* sp.) we assumed that its characteristics were those of the majority of species within the genus in Asia. When in doubt, we used a minimum score to keep the results conservative. Species were scored by three members of the project team who used life-history information from FishBase 97 (Froese and Pauly, 1997), and by two members and one additional scientist expert on Hong Kong reef fishes. For each species, the ratio of the sum of the six scores to the maximum score, expressed as a percentage, constituted the RRI.

Design Principles for an MPA/AR System.—Three sets of principles governed our design of the MPA/AR system in Hong Kong: first, biogeographic principles, aimed at maximizing ecological changes; second, statistical principles, aimed at permitting valid detection of ecological changes; and third, social principles, aimed at minimizing losses from illegal fishing.

Biogeographic Principles.—A basic principle of biogeography, the species/area curve, is widely adopted in the design of terrestrial reserves and demonstrates why the ratio of a reserve's area to its perimeter be maximized. Species-area curves demonstrating a logarithmic relationship between area and number of species have long been a basic tool of biogeography (Krebs, 1972: 530–537). Originally devised to account for the numbers of species found on oceanic islands, the theoretical model considered the balance between colonization (or immigration) and local extinction (Macarthur and Wilson, 1967). Later, the principle has been extended to ecological entities, such as nature reserves and no-take marine areas, that, by virtue of major discontinuities in habitat with contiguous areas, act analogously to islands (see, e.g., Hart and Horowitz, 1991). Species-area theory has been applied to reserves (e.g., by Boecklen, 1997) and specifically to marine reserves and artificial reefs (Bohnsack, 1991). The rate of loss of species (= local extinction) from an 'island' is related to area, absolute population size, and perimeter. Loss is proportional to area divided by perimeter, a ratio at a geometric minimum for a circle. For many types of organisms, extinctions are more common in fragmented habitats (see, e.g., Soulé et al., 1992). Colonization rates, on the other hand, are based not on 'island' geometry but on the distance (and ease of travel) to the nearest source of suitable species—another island or a large 'continental' refugium.

Therefore, first, MPAs should be circular, to minimize the loss rate, although, in practice, local topography will impose some constraints (Begon et al., 1990). Second, AR modules should be closely packed to form larger units rather than spread out over the deployment area, and they should be located near sources of colonizing individuals, ideally near sources of both adults and juveniles/larvae.

Corridor theory (see, e.g., Gilbert et al., 1998) is a third important design feature for terrestrial reserves and is relevant for planning marine reserves because reef species may not leave cover for barren trawled areas. Without protected corridors, no-take reserves may act more like isolated islands, so the disadvantages of small size such as restricted gene flow and local extinction cannot be mitigated by assured recolonization. Schmeigelow (1997) says, "All reserve designs have ecological and economic trade-offs that should be explicit in planning and implicit in monitoring. Corridors, with their emphasis on maintaining connections, reinforce the need for integrated management of reserve and non-reserve areas, if the objective of establishing healthy populations and self-sustaining ecosystems in reserve networks is to be realized." Protected corridors, however, may be difficult to enforce.

STATISTICAL PRINCIPLES.—Replication is essential for statistical validation of changes after the establishment of the MPA/AR system. A world-wide review of ARs (ERM, 1997) shows that they have generally been established with almost no thought to how their effects might be monitored scientifically. Another major consideration in design is the ability to assess and learn from the performance of the MPA/AR. For example, design that allows us to estimate migration rates will improve the simulations. Fishery openings will aid evaluation, provided they are adequately controlled.

SOCIAL AND ECONOMIC PRINCIPLES.—Economic trade-offs in reserve design are reviewed by Sumaila (1998a), but it is becoming increasingly clear that management of marine areas only works with the consent of the people affected (Beaumont, 1997; Sumaila et al., in press). It is unlikely that jurisdictions can ever provide enough police or money to enforce regulations in the seas (Haggan, 1998). Solutions are seen as a local and community role in management and a sense of community ownership in the adoption of policy goals and in sanctions to encourage compliance (Pinkerton, 1989; Pinkerton and Weinstein, 1995; Brown, 1998; Jentoft, 1998). Design of the MPA/AR system in Hong Kong has therefore attempted to take account of these requirements.

ENGAGING THE SUPPORT OF LOCAL FISHING COMMUNITIES.—In 1996 an experimental AR in Hong Kong that had attracted large reef fish was reportedly fished out by local fishers (Morton, 1996). Therefore, from the outset, engagement of the support of local fishing communities in Hong Kong was included in planning. Experience in the region (Russ and Alcala, 1989; Pomeroy, 1995) and elsewhere (Neis, 1995) shows that, without this support, likely benefits will be quickly eroded by noncompliance. Two sets of 10 public forums involving 16 fishers' organizations were held (ERM, 1999). In November 1997, the first stage introduced the concept and issues, supported by a video and brochure, and received concerns and comments. The second stage, in March 1998, also supported by a video, sought comments on specific locations, designs, and management plans. In addition consultations were held with 15 SAR government departments, five quasi-autonomous nongovernmental organizations (quasi-NGOs or 'quangos'), 11 university and conservation groups, and 20 groups representing shipping interests.

RESULTS

ESTIMATING THE BENEFITS OF MPA/AR SYSTEM

Ecosystem Modeling.—Figure 1 illustrates our principal results for fished groups in the ecosystem. Forecast biomass and catch for seven key ecosystem groups after 30 yrs is plotted relative to the present (1996) biomasses listed in Table 1. Three scenarios are plotted: the status quo with no MPA/AR, MPA/ARs comprising 10% of the total area, and

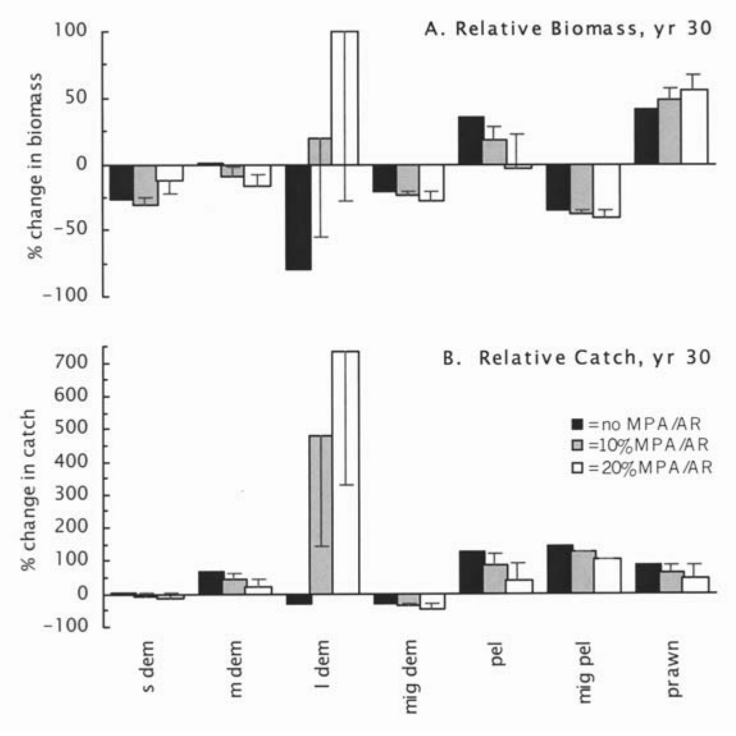

Figure 1. Simulation results for seven fished groups after 30 yrs in the Hong Kong ecosystem. Forecast biomass (A, upper) and catch (B, lower) is plotted relative to the present (1996) biomass. Three scenarios are plotted: the status quo with no MPA/AR (solid column), 10% MPA/AR (grey column), and 20% MPA/AR (open column). Results are shown for 'slow' migration assumptions in the model (see text): differences for 'fast' migration assumption are indicated by bars. Functional species groups in the model were: s dem = small demersal fish; m dem = medium demersal fish; l dem = large demersal fish; mig dem = migratory demersal fish; pel = pelagic fish; mig pel = migratory pelagic fish; prawn = penaeids. For further details see text.

MPA/ARs comprising 20%. Results are shown for the 'slow' migration assumptions. Differences for the 'fast' migration assumption are indicated by bars.

Without MPA/ARs, biomass for small, large, and migratory demersal fishes and migratory pelagics declined, probably because of our 3% annual increase in fishing mortality (Fig. 1A). Groups heavily preyed upon by these harvested groups, such as pelagic fish and prawns, increased in biomass—a food-web response. For the same reason, medium demersal fish showed little change in biomass. An increase in pelagics is a common result of heavy fishing on demersals.

At first sight, it is surprising that the decline in the biomass of some groups was not reflected in significantly reduced catch forecasts (Fig. 1B)—catches of small, large, and migratory demersal fish are not much reduced under the no-MPA/AR scenario. This phenomenon is recognized as contributing to the loss of many fisheries. Within our model it comes about because fishing mortality increases and catches are therefore maintained despite declining biomass. In real fisheries, it also occurs because some species continue to aggregate in high-density, readily catchable schools, even as their biomass declines dangerously (Pitcher, 1995, 1997; Mackinson et al., 1997). Changes in biomass are not

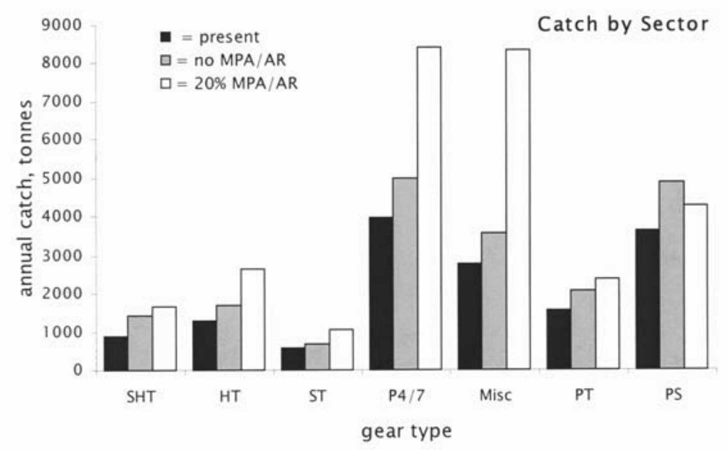

Figure 2. Annual catch in the Hong Kong fishery by gear sector as forecast by ecosystem simulations. Present day (solid columns), after 30 yrs with no MPA/AR (grey columns), and after 30 yrs with MPA/AR (open columns). HT = Hang trawler, PT = Pair trawler, SHT = Shrimp trawler, ST = Stern trawler, PS = Purse seine, Misc = Vessels that operate different gear types (longline, handline, gill net, cage trap); P4/7 = Small vessels operating mainly handline and trap.

detected until the fishery fails catastrophically (see Hutchings, 1996). We believe, therefore, that this is a realistic model response.

Catches of pelagics and prawns increased from 41 to 50% under the no-MPA/AR scenario. Forecast catch by fishing sector is shown in Figure 2. All sectors increased their catch; the purse seiners (35%), pair trawlers (34%), and shrimp trawlers (63%) showed the greatest gains. The small vessels (categories P4/7s and misc) increased their catch by about 20% despite large shifts in species composition because they employ a wide range of gears. The model suggests that, without MPA/ARs and with increasing effort, the total catch from Hong Kong will actually rise 25% to about 20,000 mt, but this increase will be accompanied by major shifts in species composition. The model clearly shows why fisheries can continue to make profits in the face of the most drastic ecosystem depletion.

Why does the simulated catch not decline as a result of stock collapses and species shifts, as appears to have happened over the past decade? The ecosystem model is capable of generating decreases in biomass and catch for functional groups: in this work it did so for some groups when fishing effort was not allowed to rise each year. Perhaps fish catch in the South China Sea has reached a position down the food web occupied by such high-turnover, low-trophic-level species that they are unlikely to be subject to recruitment collapses in the same way as traditional long-lived demersal fishes.

Figure 1 shows that, as the MPA/AR proportion increased, the reserve progressively mitigated most of these changes and shifted the species composition of both the ecosystem and the catch back toward demersal fish. Even under the fast-migration option, the same trend was seen, except that the large demersal group suffered progressively smaller losses rather than making larger gains. In Figure 1 we can see that the rise in pelagic fish biomass was halted by the 20% MPA/AR, although prawns still showed a small increase. The big increase in large demersals prevented small and medium demersals, their main prey, from changing very much in either catch or biomass. The catch for this group of high-value fishes rose under all migration-speed options.

In the 20% MPA/AR scenario all sectors showed an increase in catch. The most spectacular increases were in the small-vessel sector (Misc: 200%; P4/7s: 112%), but prawn trawlers and pair trawlers showed rather small increases, whereas purse seiners showed a decrease compared to the no-MPA/AR option. The total annual catch forecast doubled compared to the present day to about 29,000 mt, and the species composition of the catch shifted strongly toward demersal species (percentage pelagic halved to 26%).

At first sight, this finding appears to raise a barrier to implementing the MPA/AR system, as the sectors most likely to benefit are small-scale fishers, who are relatively unorganized and do not have a strong lobby. As demersal fish recover, however, larger-scale commercial fishing of these high-value fish, which are much in demand in Hong Kong, will probably shift the emphasis of the present-day fishing sectors, which have adapted to making a profit in a heavily depleted system.

The results for the 'medium' and 'fast' migration show that, as migration speed increases, and with it the rate of exchange between the MPA and the fished non-MPA area, the benefits of the MPA are reduced. At the high migration speeds, the MPA biomass is no longer much protected against increasing fishing pressure, because individuals move outside the MPA more frequently and are quickly caught. Uncontrolled fishing (or cheating) in the MPA area also rapidly erodes the advantages.

Reef Response Index (RRI)

Of the 152 species scored, 108 (71%) received RRI scores below 33%, suggesting that we could not find life-history criteria supporting increased production from ARs. Of those species receiving low scores, 61 (56%) had insufficiently complete life-history data for assessment. Of those receiving scores higher than 25%, the median score was 66%. The highest-scoring species were in the families Pomacentridae, Muraenidae, and Palinuridae.

Figure 3 (solid columns) shows the distribution of RRI scores for six fish groups from the ECOPATH model. Most pelagic fish have lower RRIs; most demersal fish have higher ones. Although the largest number of high RRIs were found among the demersal groups, RRI had no straightforward relationship with reef-related life-history characteristics. For example, the small demersal fish group contained members of the high-scoring Pomacentridae (damselfish) but also the low-scoring Leiognathidae (pony fish). Revised modeling might split the groups into reef-related and reef-unrelated groups on the basis of RRI.

About 105 species are known, from dive surveys and the like, to be present in very low numbers in Hong Kong, but are not represented in the reported catch of 152 species. When these species increase in numbers as a result of the MPA/AR, if they were to shift the distributions of RRIs for an ECOPATH group, the simulation modeling would clearly be biased, but Figure 3 shows that adding these new RRIs (open columns) to the six main ecosystem groups does not alter the distributions. Nevertheless, the assumption that these species are all recruited eventually to the biomass and catch would improve the ecosystem model, so the diet matrix might be altered accordingly.

The Design of an MPA/AR System in Hong Kong

On the basis of the principles set out in the methods, we used four specific design features for the MPA/AR system in Hong Kong: no-take artificial reefs, no-take corridors, fished artificial reefs, and managed buffer zones.

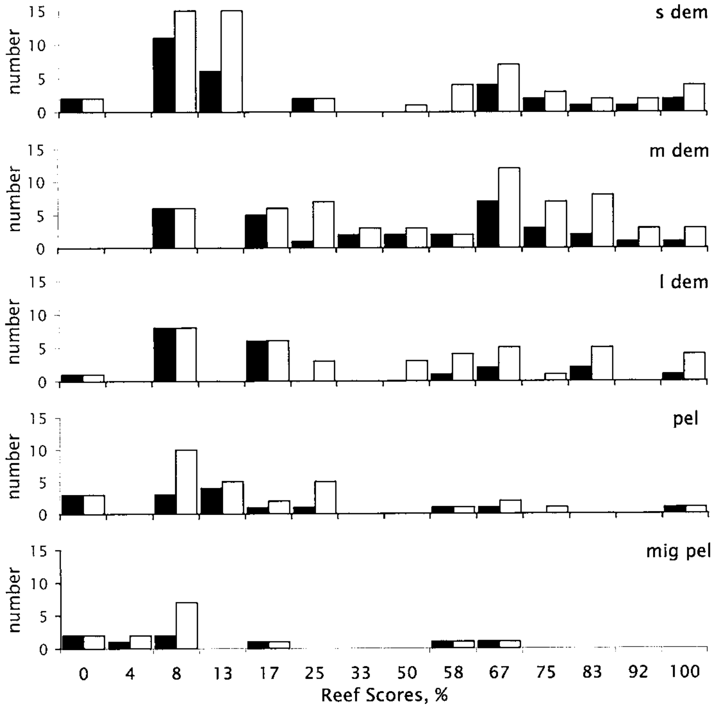

Figure 3. Distributions of Reef Response Index for six fish groups in the ecosystem simulations. The RRIs for fish species in the model (solid columns) are compared with total for all species reported present in 1996 from Hong Kong (open columns).

Feature 1: No-Take Artificial Reef.—No-take ARs are engineered to maximize settlement of benthic organisms and eventually corals, to provide food and shelter for high-value commercial fishes, to provide refugia from fishing, to inhibit the use of trawl gear, to minimize danger to marine traffic and scuba divers, and to be robust and stable in the face of local water currents and substrate. The immediate AR area must be designated a 'no-anchor zone', so that anchors will not damage the AR structures. Moreover, the immediate AR site must be designated a permanent 'no-take' zone for commercial fishing, spearfishing, angling, shellfish harvesting, and other consumptive use of marine resources; the ecological benefits depend on it. Recreational use, exclusive of fishing, could be controlled by license, although we suggest that in the early years disturbance to colonizing organisms be limited to monitoring or educational activities.

The use of an extended buffer zone, the MPA, around the AR deployment sites is vital, not only to ensure maximum benefit from ARs but also to allow for surveys to establish density gradients that could be useful in determining migration rates used in the simulation modeling.

Feature 2: No-take Corridor.—The importance to the rebuilding process of ecological connectance, allowing fish to colonize and migrate among ARs, was recognized at public forum consultations in Hong Kong. It can be implemented by protected no-take corridors between reefs. Fishing would not be allowed in the no-take corridors, but other uses, such as passage or anchorage of shipping, passage of underwater cables, and the like, should not affect their ecological function.

Pairs of ARs connected by 'no-take' corridors provide insurance against the risk that one of them might be damaged by some catastrophic event. Second, pairs provide replicates for statistical analysis of the rebuilding. Once singletons are ruled out, application of the maximum-species-in-an-area principle (see Methods) shows that, for a given amount of AR structure, pairs of ARs are a better design than groups of three, four, or more. Given the need for replication and insurance, pairs maximize the area-to-perimeter ratio and therefore the niches for benthic reef-colonizing organisms, which in turn, increase fish biodiversity. Figure 4a illustrates an MPA/AR design with features 1 and 2.

Feature 3: Fished Artificial Reef.—From an ecological point of view, artificial reefs subjected to fishing might endanger the recovery of fish stocks or, by attracting and concentrating resources, make matters worse, but a management plan that allows some reefs to be opened for fishing has three advantages. First, fishing on the artificial reefs is perceived as important to the fishers' life style; allowing fishing will encourage support from the fishers' community. Second, fished reefs provide a contrast in the data and controls for monitoring. Third, permitted fishers may act to enhance monitoring and enforcement. These social and information advantages may balance the loss of ecological benefits.

The idea of the MPA/ARs as no-take sanctuaries could be promoted through visits by Hong Kong fishers, together with scientists and government staff, to areas where community management has increased fish stocks. This idea attracted much attention at the public forum consultations.

The long-term advantages of having fishers come to regard artificial reefs as sacred and unfishable sites would be considerable, but this is not a process that could be forced. One indirect way to achieve this change in attitude would be to allow fishing on designated reefs so that fishers could clearly learn about the advantages of closure for themselves. Moreover, comparing catch on fishable ARs with catch from buffer areas around permanently closed 'no-take' ARs, through involvement of educational programs, might, over time, lead fishers to request a regime under which 'fishable' ARs become protected. For this reason our design sacrifices one reef to fishing inside each MPA Each MPA will therefore include three ARs, one of which is open to fishing, or four ARs, two of which are open, if statistical replication is thought to override concern for restoration.

The identity of any reefs open to fishing should remain constant, to prevent confusion. An alternative scheme that rotates the identity of fishable reefs would interfere with rebuilding of long-lived species and be expensive to enforce. Fishing permits for ARs should be issued only on condition of specified assistance with monitoring in the form of detailed catch reporting, providing at least the location and date and the species, numbers, and sizes of fish caught.

The use of a design where some reefs are closed and some are opened to controlled and nondestructive fishing effort offers great potential for assessment of changes in productivity, but it also poses some risks. Along any fished boundary of an unfished area, local depletion will result from gradients induced by fish movements into the protected area (Walters et al., 1999). It is also important that fishable ARs be located far enough away from closed areas, so that the fishable ARs will not 'siphon' fish away from the closed MPA/AR complex. Figure 4B illustrates an MPA/AR design with features 1, 2, and 3.

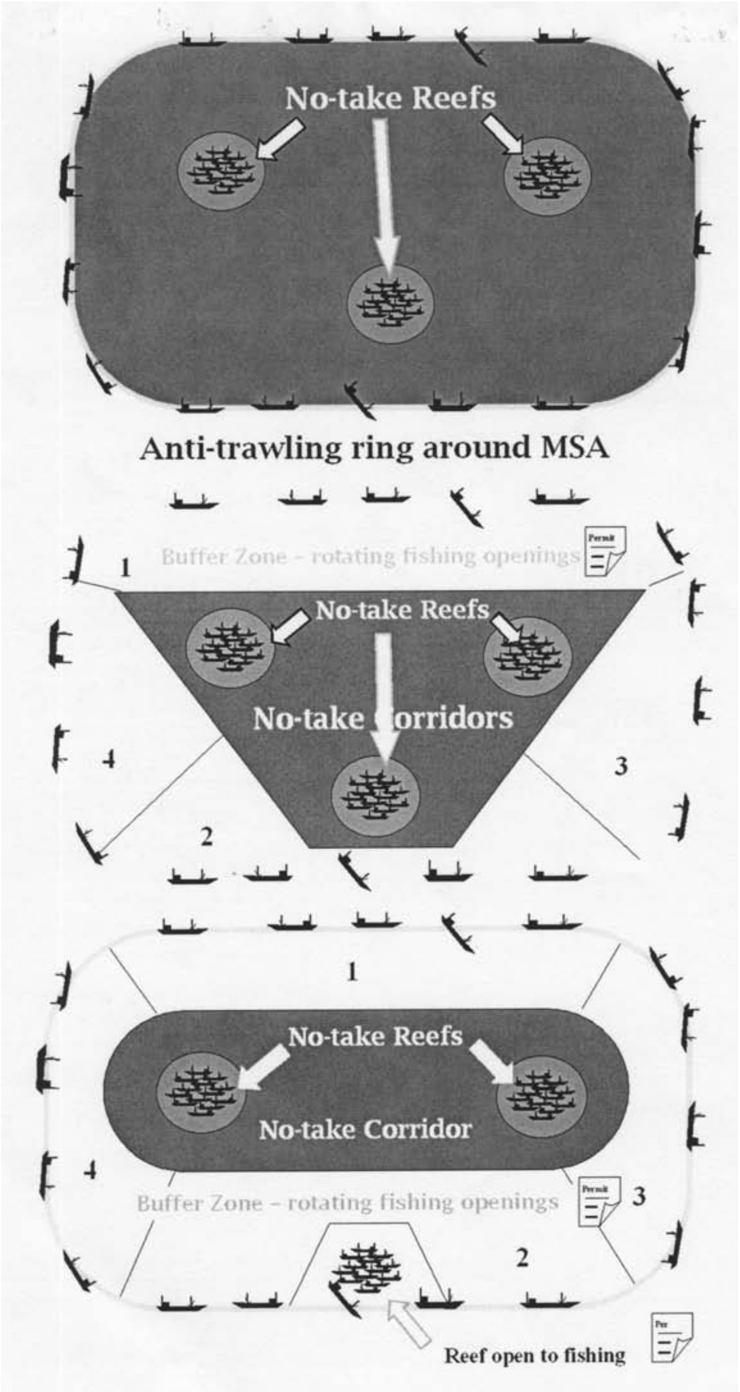

Figure 4. Spatial aspects of the design of the MPA/AR system in Hong Kong. A (upper): only ecological theory considered; (B) (middle): with the addition of monitoring requirements; (C) (lower): with the addition of social aspects to encourage compliance. (Note other reef structures are used in addition to sunken vessels.)

Feature 4: Managed Buffer Zone.—The fourth design feature is the establishment of a managed buffer zone around the core no-take ARs and corridors. The buffer zone may be divided into sectors that may be opened sequentially for fishing. From an ecological perspective, openings can be made contingent upon certain levels of fish stock rebuilding, but this policy might have to be modified by the need to retain the allegiance of fishers.

Trawling must be banned from the MPA to permit recovery of important benthic habitat and coral-reef rebuilding. It can be discouraged by the AR design (such as sunken vessels) within the buffer zone, but other maritime and recreational activities (except spearfishing and trophy angling, which defeat the purpose of the MPA) could be allowed by permit.

At the cost of slower resource rebuilding than would result from closing the whole MPA/AR, the buffer zone permits the benefits of rebuilding from the AR system to be harvested by fishers themselves earlier than might otherwise be possible; it therefore encourages support from fishers and the public. The fishing openings and closures keep fishing under close control, and fishing permits that include mandatory catch reporting will allow more thorough and rapid monitoring. The buffer-zone feature also offers much scope for experimental manipulation to improve estimates of migration rates. For example, a fish-tagging program could have local involvement. The fished artificial reef should be located within the managed buffer zone, but it must be far enough away from closed ARs not to act as a fish attraction device. The size of the unfished areas will affect the ability of stocks to rebuild, as individual species depletion within the protected area will occur through the movement of stocks. Figure 4C illustrates an MPA/AR design with all four design features.

Fishing permits issued for the buffer zone or fished reef should specify reporting requirements and catch limitations, including area and gear restrictions, minimum size of indicator species, etc. Fishers' cooperation in accurate reporting is vital to the success of this type of evaluation, as misreporting of the area where fish are caught is a dominant characteristic of noncooperative systems. Initial permit numbers can be estimated on the basis of known ecology, fishing gears, and site characteristics of each MPA/AR complex. Once baseline parameters are known from a postdeployment survey, increases can be made contingent upon resource recovery. An adaptive management plan could be designed to assist the permit-issuing system.

Local Fishing Communities

Results of the consultations (a final government round is not completed at the time of writing) are reported by ERM (1999). As expected, comments included suggestions by small-vessel fishers that ARs be located closer to the shore. Trawlers wanted compensation for loss of trawling habitat. Others wanted closed areas located away from traditional, heavily-used inshore fishing grounds. Surprisingly, however, at the end of the forum program, Hong Kong fishers were about evenly divided between those supporting design option 3, with buffer zones and regulated fishing openings, and those supporting complete no-take closures in the MPAs. Moreover, support for the initiative among fishers is growing.

Further simulations suggest that even a small amount (less than 5%) of cheating inside the no-take zones will rapidly erode rebuilding. In addition, cheating can be very selective, especially affecting longer-lived species, which are the slowest to recover, so success of the MPA/AR initiative depends critically on maintaining contact with and outreach to these fishing communities. For example a community-outreach program could include confidential telephone hotlines for reporting illegal fishing backed up by a rapid response to such reports by the authorities. Results of monitoring by analysis of dive surveys and licensed fishing reports must be reported to local communities. Fishers must also develop a sense of ownership of the regulations and enforcement by being involved in the ongoing monitoring program. These issues are being evaluated by the SAR government for ongoing support.

Discussion

Are the multispecies, ecosystem-based predictions that we have attempted here more robust than single-species work? Many marine ecologists would refuse to tackle the Hong Kong problem, considering it too complex and difficult and imbued with too many uncertainties. Moreover, our forecasts are challenged not only by statistical uncertainties from the resource survey itself but also by the major process errors deriving from the properties of real aquatic ecosystems. Clearly, after the MPA/AR system is implemented, the ecological system could have surprises in store for us, such as species substitutions, that might well not be defined by our 15 'ecopath' trophic groups. We absolutely must, therefore, monitor the system continuously and rerun the simulations in the light of changes that occur. Nevertheless, this analysis represents our best shot using the present set of tools available, and this work, we believe, represents the type of concerted action required if we are to stand a hope of actually restoring marine ecosystems and their fisheries.

At present, our approach ignores the succession of species using ARs and their interactions (see Russ and Alcala, 1996b). We would also expect that smaller, faster-growing species would be the first to make use of ARs and that, as their biomass increased, they would be the first to provide additional catch. Slower-growing species such as larger groupers and snappers would probably begin to use the ARs as juveniles, but any major change in biomass would take several years to be evident. Early indications from ARs deployed during 1998 confirm that juveniles of slower growing snappers, groupers, breams, and grunts have been the first to colonize the ARs. We need to find a better way to link RRI scores to the ecosystem simulations. Splitting the model groups into reef and nonreef species and tuning diet matrices to the new mix of recruited species should make significant improvements.

Additional uncertainty arises if the cross-validation of species responses by reef experts and the literature summarized in FishBase proves misleading. Moreover, the estimates of fish biomass and catch for Hong Kong could be made more robust by confirmatory survey and analysis (Pitcher et al., 1998).

Without a true spatial model of the Hong Kong fishery, we must make several assumptions that may be unfounded. One is that a single model adequately describes the Hong Kong fishery now and in the future. Indeed, the central premise of these models is that the basic structure of the system does not change over time. We improved our model by creating a 'Large Demersal Fish' group, which is presently not a significant part of the commercial catch but which is expected to increase in importance in the future with the MPA/ARs. This is a minor example of a way of addressing the problem of qualitative jumps in ecosystem structure. In the future, we hope to split model groups into reef-associated and non-reef-associated species groups using the RRI scores as suggested above.

We also plan to address the problem by constructing models of past Hong Kong marine ecosystems using the “Back to the Future” approach. Alternative ecosystem models may also be found by examination of existing habitats in the South China Sea where such severe degradation has not occurred, for example in the Dengan Dao (Lema) islands to the south of Hong Kong, where reef habitats are reportedly in reasonably good condition (K. Wilson, pers. comm.).

A second major assumption is that the biomass of all ecosystem groups is distributed uniformly over the area of Hong Kong. This is unlikely to be true, and the model we used is an average combining the estuarine western and oceanic eastern environments in Hong Kong. More precise spatial information needed to partition the model is sparse for most fish species at present. Moreover, our lack of precision in estimating migration rates does not allow us to make firm estimates of the effects of MPA/ARs.

The annual increase in fishing mortality of 3% in our simulation modeling eroded the biomass, and eventually the catch, of many ecosystem pools. Clearly, we would have produced more optimistic results had we not included this factor, but for most scenarios, the effect was at least mitigated by the use of the MPA/ARs. If fishing pressures could be held constant, or even reduced, for example by a ban on trawling, we can show that the biomass of most groups would increase faster and a more mature system would evolve, where top predators form a larger part of commercial catches and where biomass levels are better able to cope with environmental instability.

Although the physical presence of ARs does make some fishing methods, like trawling, more difficult or dangerous, it may actually assist small-scale fishers. For this reason the design of the MPA/AR system is critical to success. Although the complete MPA/AR closure in design of Figure 4A may be enthusiastically received by environmentalists, it is unlikely to be entertained by fishing communities, who may see all or most of their traditional grounds sequestered, i.e., feel that they are bearing a disproportionate share of the cost of conservation. The design in Figure 4B is better in that it preserves the integrity of the MPA/AR complexes and connecting corridors while allowing sequential access to buffer zones where fishing should be improved by migration from the reef sanctuary area. The design in Figure 4C satisfies anticipated demand for ‘fishable ARs’, an outcome of the community consultations in Hong Kong. It will, however, be vitally important that fishable ARs be linked to permits setting out access and gear limitations and the requirement to monitor catch and size.

In Hong Kong, the implementation of design features from option 3 at specific sites is in the final public consultation phase; HK$100 million funding is secured. Seventeen potential sites have been assessed on the basis of five ecological, three economic, and three social criteria (ERM, 1999). Five Marine Special Areas (i.e., MPA/AR sites) are currently being considered. One option is to sink 60 vessels, the most cost-effective AR modules, to form AR complexes in each MPA according to the design criteria, but other structures, including concrete, rock, and coated tires, are also being considered. It has been recommended that ARs be emplaced within offshore MSAs because of the difficulties encountered in reducing fishing effort and declaring MSAs at traditional coastal rocky-shore fishing grounds (Wilson and Leung, 1998). However, it would be disappointing if, as in the original plan, of the 10.3% of the Hong Kong area included in MSAs, only about 4% were to be permanently no-take. With the cooperation of local fishing communities, perhaps more is politically achievable. Moreover, our modeling suggests that less than 10% no-take may be insufficient for major benefits to accrue fast enough for continued public support. Moreover, this proportion may itself be split into five areas, so peripheral losses will be greater than in the ecosystem modeling, which assumed one MPA area.

The results from the ecological modeling for this project were used to carry out a bioeconomic analysis to determine the economic consequences of the different scenarios explored (Sumaila, 1998b; ERM, 1999). Major uncertainties were maintained in the bioeconomic projections, which examined the range of MPA/AR enhancements and retained the projected increase in fishing power each year. The discount rate, the operating costs and profits for each fishery sector, the costs of deploying the MPA/AR system, and the costs of monitoring and enforcement under a range of scenarios were evaluated. Scenarios examined a range of options for illegal fishing inside the MPAs and associated costs of community-based monitoring and enforcement. The overall result, using the most conservative set of ecological assumptions, but with cheating minimized through an aggressive program of community involvement and 24-hour enforcement, suggested that Hong Kong's fishery could provide, over 30 years, an additional 50% (US$150 million) of discounted profit (ERM, 1999).

This system has been designed so that monitoring what happens in the MPA/ARs, and to the fishery catches, can generate adjustments to the model and update the simulation forecasts. Bortone (1998) reviews mixed experiences with previous AR research, and we are painfully aware both of the shortcomings of our work and of the uncertainties affecting final implementation. Nevertheless, our analyses suggest that the attempt to establish MPA/ARs in this, one of the most devastated oceans of the world, will be worthwhile.

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